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by

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INVESTIGATION OF THE X RAY EMISSION OF SOLAR FLARES BY THE RADIOASTRONOMICAL METHOD *

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Tom 29, 152-159,
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by Yu.I.Neshpor

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ABSTRACT

On the basis of a study of the frequency dependence of the weaking of cosmic radio emission during sudden ionospheric disturbances, the following conclusions have been arrived at :

1. The spectral distribution of the intensity of X-ray emission of solar flares is different for various flares.

2. Some of them are characterized by an apprreciable increase in the intensity of X-ray emission in the short-wave region (0.1 ÷ 1 Å)

AUTHOR

* * *

Rocket measurements [1, 2] and indirect methods of investigation of the D-region of the ionosphere [3, 4], point to the fact that an appreciable increase of shortwave radiation is observed in the emission of some solar flares, causing substantial variations in the terrestrial ionosphere. The study of the spectral composition of this radiation and of its temporal variation offers a substantial interest from both, the astrophysical and geophysical points of view.

For the investigation of flares' hard radiation the method of asborption measurement in two frequencies can be applied.

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* [Issledovaniye rentgenovskogo izlucheniya solnechnykh vspyshek radioastronomicheskim metodom]

Study of frequency dependence of signal weakening during SID [5, 7] allows the judging of absorption layer position. And since the penetration depth of flares' X-ray emission and the height of the surplus absorption are directly interrelated, we may obtain, by studying the frequency dependence of radiowave absorption, a certain number of data on the spectral distribution of that radiation.

DEPENDENCE OF ABSORPTION ON FREQUENCY

Currently a radioastronomical method is broadly applied for the study of frequency dependence of signal weakening [5 – 8]. It consists in registering of the intensity of cosmic radio emission in several frequencies.

The field strength of the received radio emission E and the medium's absorption factor, are linked by the following correlation (see ref. [9]):

$$\ln \frac{E}{E_0} = -\int k(z)\,dz, \qquad (1)$$

where E_0 is the field strength in the absence of absorption;

$$k(z, t) = \frac{2\pi e^2}{mc} \frac{N(z, t)\,\nu(z)}{\nu^2(z) + (\omega + \omega_L)^2},$$

$N(z, t)$ is the electron density; $\nu(z)$ is the collision frequency; m and e are respectively the charge and the mass of the electron; c – the speed of light, ω is the operation frequency; ω_L – the gyrofrequency.

It was shown in [5] that when the X-ray emission of flares penetrates to heights where $\nu^2 \geqslant \omega + \omega_L$, there may exist, depending upon the form of the curve $N(z, t)$, a dependence of surplus absorption on frequency in the form:

$$\frac{\Delta\rho_{\omega_1}}{\Delta\rho_{\omega_2}} = \left[\frac{\omega_L + \omega_2}{\omega_1 + \omega_L}\right]^n,$$
$$0 \leqslant n \leqslant 2$$

where $\Delta\rho_{\omega_1}$ is the surplus absorption in the frequency ω_1, $\Delta\rho_{\omega_2}$ is the surplus absorption in the frequency ω_2.

Besides, as was noted in [5], if the increase in ionization takes place mostly in a layer that is thin by comparison with the quiet D-region, we can write for the layer where

$$\nu_1\nu_2 = (\omega_2 + \omega_L)(\omega_1 + \omega_L), \tag{2}$$

the relation

$$\frac{\Delta\rho_{\omega_1}}{\Delta\rho_{\omega_2}} = \frac{\omega_2 + \omega_L}{\omega_1 + \omega_L}. \tag{3}$$

ν_1 and ν_2 being the values of collision frequency at boundaries of the disturbing layer.

In order to study the frequency dependence of signal weakening (determination of the position of the surplus absorption), we used the data on absorption of cosmic radio emission in two frequencies : 26.7 and 32.5 mc/s [8]. During the period from April 1960 to August 1961 more than 20 cases of sudden increase in cosmic radio emission were registered.

In Table 1 next page, we present 17 cases for which the ratios of surplus absorptions are determined in the maximum of ionosphere effect in two frequencies. For operation frequencies of 26.7 and 32.5 mc/s and provided the electron density increase takes place in the region where $\omega \gg \nu$, the ratio of surplus absorptions is

$$\frac{\Delta\rho_{\omega_1}}{\Delta\rho_{\omega_2}} = \left(\frac{\omega_2 + \omega_L}{\omega_1 + \omega_L}\right)^2 = 1{,}46.$$

As may be seen from the Table, the weakening in intensity of cosmic radio emission during certain (dates underlined) SID, is inversely proportional to operation frequency, i.e. correlation (3) is being adhered to. Utilizing the expression (2) and also the data on altitude distribution of collision frequency $\nu(z)$ [10], we may conclude that the increase in electron density for the effects noted took place mainly in the 40 – 60 km region.

TABLE 1

DATE	COMMENCEM.	MAXIMUM	END	$\Delta\rho f = 26{,}7$ $\Delta\rho f = 32{,}5$
1.IV 1960 r.	11^h51^m—11^h52^m	12^h05^m		1,20
29.V	10 39 —10 40	10 45		1,46
8.VI	10 41	10 50	11^h20^m	1,27
13.VI		10 42		1,46
26.VI	16 58 —17 00	17 12	18 00	1,46
27.VI	14 49	14 58	15 30	1,40
14.VII	13 57	14 00	14 20 —14 30	1,42
20.VII	13 23 —13 24	13 32	13 54	1,35
7.VIII	10 25 —10 26	10 38	11 50	1,44
7.VIII	15 19 —15 20	15 22		1,22
14.VIII	16 06	16 09	16 35	1,65
19.VIII	15 38	15 50		1,46
14.IX	13 03 —13 04	13 10		1,46
19.IX	9 59	10 08		1,32
10.XI	13 17	13 29	15 40	1,57
12.XI	16 26	16 30	17 15	1,20
18.VII 1961 r.	12 43 —12 44	13 14	14 30	1,20

DEPENDENCE OF IONIZATION EXCESS ON ALTITUDE

As a result of absorption by the medium of a single X-ray quantum [11], there are formed :

$$\frac{h\nu - 500}{i} = i(\lambda) \text{ pairs of ions.}$$

where $h\nu$ is the energy of a quantum; 500 is the binding energy ; ε_i is the quantity of energy necessary to form one pair of ions.

The total number of ion formation events at the altitude z will then be

$$I(z) = \int_{\lambda_1}^{\lambda_2} \left(1 - \frac{500}{h\nu}\right) \frac{\sigma(\lambda)\, n(z)}{e_i} S_\infty(\lambda)\, e^{-\tau(\lambda z)}\, d\lambda, \qquad (4)$$

where λ is the wavelength; $\sigma(\lambda)$ is the effective photoionization cross section; $\tau(\lambda, z)$ is the optical thickness; $S_\infty(\lambda)$ is the flux beyond the atmosphere.

It may be seen from the expression (4) that if the dependence of the flux $S_\infty(\lambda)$ on the wavelength is known, we may plot the relative variation of ion formation function with the height [12], i.e.

$$\varphi(z) = \frac{I(z)}{I(z)_{z=z_m}}, \qquad (5)$$

where $I(z)_{z=z_m}$ is the maximum value of the function of ion formation.

In order to determine the dependence of the surplus (excess) ionization on altitude, we shall utilize the standard balance equation [11]. Assuming that the effective recombination coefficient does not depend on altitude in the 40 — 80 km range, we shall obtain

$$N(t, z) = \sqrt{[x^2(t, z)_{\substack{t=t_m \\ z=z_m}} - 1]\, N^2(0, z)_{z=z_m} \varphi(z) + N^2(0, z)}, \qquad (6)$$

where $N(t, z)_{t=t_m}$ is the value of electron density at the altitude z; $x(t, z)_{t=t_m}$ is the relative increase in electron density at the altitude z_m; $N(0, z)$ is the value of electron density during the quiet state of the ionosphere; f_m is the time of ionosphere effect maximum. It may be seen from (6) that if the model of undisturbed ionosphere and the relative variation of electron density at the altitude z_m are known, we may plot, for a specific form of $S_\infty(\lambda)$ [Or $\varphi(z)$] of the X-emission, the distribution of excess ionization in time of SID, and consequently, we may also compute the value of total absorption.

SPECTRAL DISTRIBUTION OF THE INTENSITY OF X-RAY EMISSION

1. Methodical Part.

The determination of the function $S_\infty(\lambda)$ was effected by the comparison method of results computed with those of observations, making use of the correlations (1), (4)— (6). The distribution of $N(0, z)$ was given in the form of the exponential $N(0, z) = 100 \cdot e^{0.23(z-70)}$ [12]. The selection of the distribution function of the initial value of electron density has no principal significance, for in the 40— 60 km altitude region the value $N(O,z)$ may be neglected by comparison with that of $N(t,z)_{t-t_m}$. The latter was so selected for the given $\varphi(z)$, i.e. for $S_\infty(\lambda)$, that the value of the excess absorption in the frequency of 26.7 mc/s

$$\Delta\rho = \frac{2\pi e^2}{mc}\int\limits_z \frac{[N(t, z) - N(0, z)]\,\nu(z)}{\nu^2(z) + 4\pi^2(26{,}7 + f_L)^2}\,dz$$

be corresponding to the experimentally measured value $\Delta\rho_{f=26.7}$ at time of the SID. Then we computed the absorption in the frequency of 32.5 mc/s, finding the ratio of excess absorptions

$$\frac{\Delta\rho_{f=26.7}}{\Delta\rho_{f=32.5}}.$$

From the comparison of the results obtained with those of observations we derived the conclusion on the spectral intensity distribution of X-ray emission of the flare.

With the view of corroborating the possibility of applying the proposed method of $S_\infty(\lambda)$ determination, it interesting to consider the ionosphere disturbance of 19 August 1960. An increase by 2.3 times in the flux of shortwave radiation was registered in the 8 — 21 Å wavelength region aboard the 2nd spaceship-satellite between 15^{45} and 15^{54} hours Moscow time. As a result of the effect of this shortwave radiation an increase in electron density [11] (absorption increase) must take place in the region above 75 km. The time interval (15^{45}— 15^{54}) corresponds to ionosphere effect maximum (15^{50} hrs). The measurement of intensity of cosmic radio emission in two frequencies

$$\left(\frac{\Delta\rho_{f=26.7}}{\Delta\rho_{f=32.5}} = 1{,}46\right)$$

shows that the increase in absorption mainly took place in the region above 75 km, which agrees well with [1]. Therefore, we are in a position to judge about the character of shortwave radiation of solar flares by studying the frequency dependence of radiowave absorption.

2. QUANTITATIVE ESTIMATES

T. Chubb and H. Friedman with their associates have measured the X-ray emission spectrum during the flare of 31 August 1959 [13]. Using these data, Whitten and Poppoff [14] plotted the distribution of excess ionization as a function of altitude (Fig. 1). As may be seen from that Figure, the increase in electron density took place mainly above 70 km. Since for the SID recorded in Table 1 the increase of excess absorption took place at the 40 – 60 km level, the spectral distribution of the intensity of shortwave radiation of flares having caused these ionosphere effects apparently has another character. To corroborate this assumption we shall examine the SID's of 1 April and 12 November 1960. The distribution of excess ionization in the assumption that the emission of the flare takes place only within a narrow, strictly defined wavelength range, is plotted in Fig. 2 (solid curves). The intensity variations in each of these intervals correspond to the variation of spectrum intensity in the same band [14], i.e. if we should broaden this wavelength range, we would obtain a spectrum published in [14].

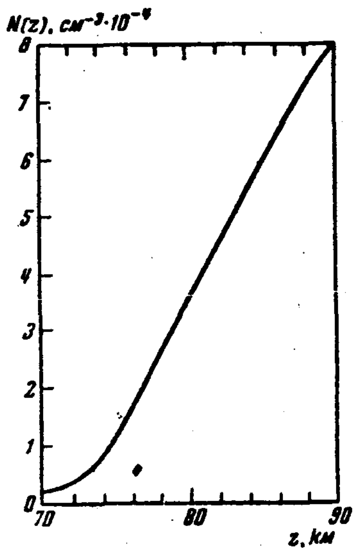

Fig. 1.- Dependence of electron density on altitude obtained in [14] for the SID of 31 Aug. 1959

The curves N (z) of Fig. 2 are plotted for the corresponding bands with the view that (appropriate selection of $x(t, z)_{\substack{t=t_m \\ z=z_m}}$), that the total excess absorption be equal to the maximum value measured during SID in the frequency of 26.7 mc.s. Then we computed the absorption in the frequency of 32.5 mc.s. The ratios

$$\frac{\Delta\rho_{f=26,7}}{\Delta\rho_{f=32,5}}$$

are plotted in Table 2.

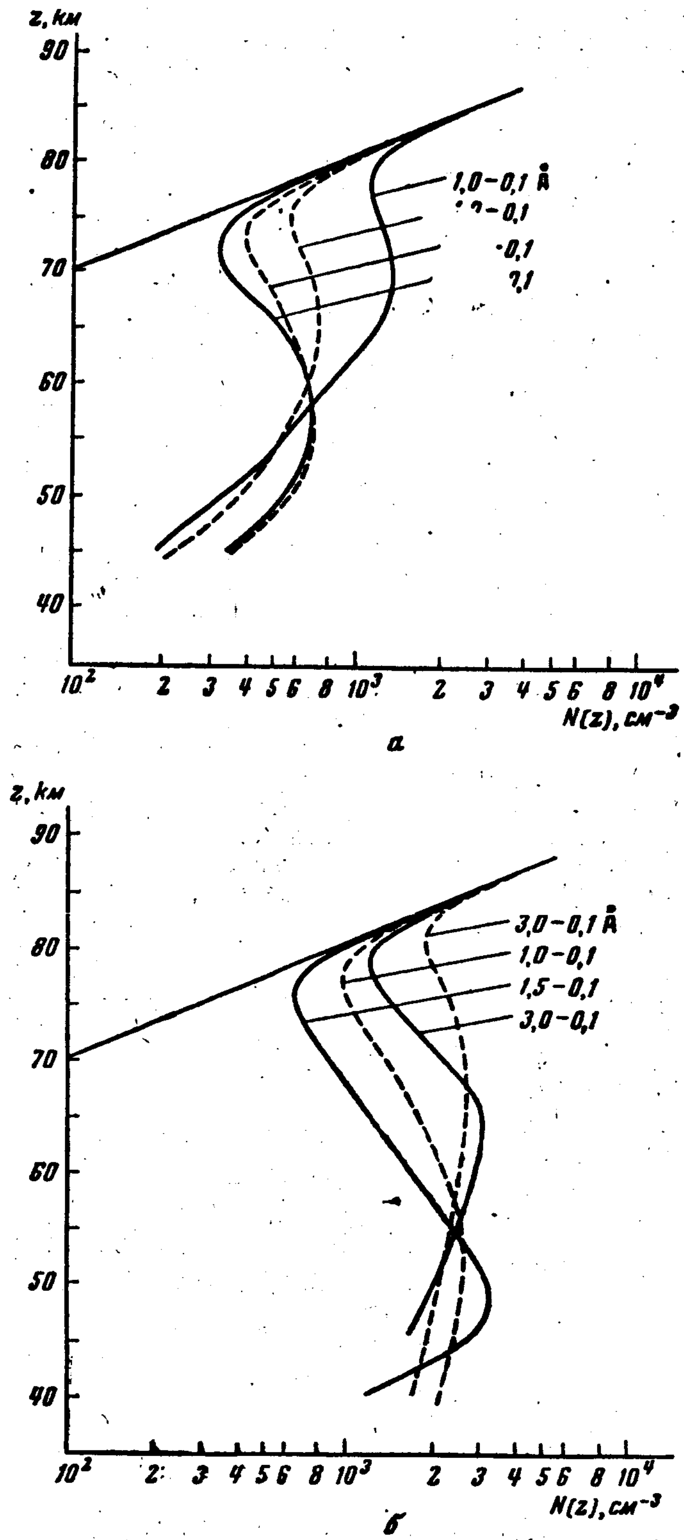

Fig. 2. - Dependence of electron density on height for the ionosphere disturbance of 12 November 1960 (a) and for that of 1 April 1960 (б).

TABLE 2

DATE 1960	Chubb a. Friedman band	ratio	$S_\infty(\lambda)=f(\lambda)=const$ band	ratio	Experiment $\frac{\Delta\rho_{f=26.7}}{\Delta\rho_{f=32.5}}$
Nov. 12	1.0 — 0.1 Å	1.345	1.0 — 0.1 Å	1.293	~1.2
	0.5 — 0.1	1.273	0.6 — 0.1	1.270	
	0.3 — 0.1	1.235	0.2 — 0.1	1.245	
Apr. 1	3.0 — 0.1	1.292	3.0 — 0.1	1.262	~1.2
	1.5 — 0.1	1.214	1.0 — 0.1	1.234	

It may be seen from Table 2 that the best agreement of the computation data with those of observations takes place in the assumption that the X-radiation is emitted in the 0.3 — 0.1 Å range (12 Nov.) and in the 1.0 — 0.1 Å band (1 April). This agreement is disrupted as the band widens. Consequently, the ionosphere effects of the type of those of 12 November and 1 April 1960 cannot possibly be explained by X-ray radiation with the spectral distribution of [14]. On the basis of that, we may apparently reach the conclusion that the spectral distribution of X-ray radiation of flares is different for various solar flares.

If we further assume that the X-ray emission of flares is due to bremstrahlung of highly-energetic particles [15], it is hardly probable that the spectrum of shortwave radiation will be limited to the long-wave region. That is why attempt is made by us to explain the ionosphere effects of the type observed on 1 April by a spectrum with maximum intensity value in the 0.3 Å region. At the same time, the variation of shortwave radiation intensity in the soft radiation region is inversely proportional to the square of the length of wave $\left(S_\infty(\lambda)\propto\frac{1}{\lambda^2}\right)$, and in the hard radiation region — proportional to wavelength $(S_\infty(\lambda)\propto\lambda)$. The computation of excess absorptions of $\left(\frac{\Delta\rho_{f=26.7}}{\Delta\rho_{f=32.5}}=1{,}236\right)$ points to the good agreement with the observation data of $\left(\frac{\Delta\rho_{f=26.7}}{\Delta\rho_{f=32.5}}\approx 1{,}2\right)$

Therefore, the ionosphere effects of the type of 1 April 1960 may be explained by the spectrum represented in Fig. 3 [next page].

If we now assume that the position of the maximum value of $S_\infty(\lambda)$, just as the inclination of the dropping ramifications (Fig. 3) may vary, the different ionosphere effects can be explained, and the spectrum, presented in ref. [14] can be obtained.

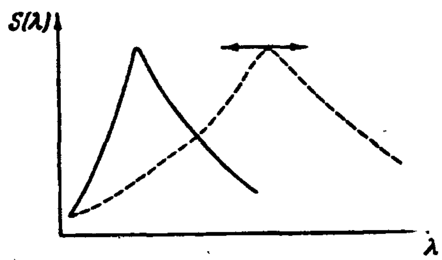

Fig. 3.- Dependence of the X-ray flux on the wavelength.

Inasmuch as on the basis of study of SID's no strictly specific deductions on the spectral distribution of shortwave radiation can easily be made, conceptions are introduced in regard to the effective X-radiation band, i.e. the true distribution of $S_\infty(\lambda)$ is approximated by a rectangular distribution in the a certain wavelength range

$$\int_{\lambda_1}^{\lambda_2}\left(1-\frac{500}{h\nu}\right)\frac{\sigma(\lambda)n(z)}{\varepsilon_i}S_\infty(\lambda)\,e^{-\tau(\lambda,z)}\,d\lambda = S_\infty\int_{\lambda_1'}^{\lambda_2'}\left(1-\frac{500}{h\nu}\right)\frac{\sigma(\lambda)\,n(z)}{\varepsilon_i}\,e^{-\tau(\lambda,z)}\,d\lambda.$$

The dependence of electron density on altitude is represented in Fig. 2 by dashed lines. The values of ratios of excess absorptions in two frequencies $\frac{\Delta\rho_{f=26,7}}{\Delta\rho_{f=32,5}}$ for the corresponding bands ($S_\infty(\lambda)$) are compiled in Table 2. It may be seen from the Table that the solar flares having caused the ionosphere effects of 12 November and 1 April 1960, were attended by rather hard shortwave radiation (0.1 — 1.0 Å).

Before making final conclusions, it is necessary to take note of the following. We made the assumption of the fact that the effective recombination coefficient ($\alpha_{eff}(z)$) does not depend on altitude in the lower region D of the ionosphere. The accounting of the dependence of $\alpha_{eff}(z)$ on altitude may only lead to the fact that the effective X-ray band of the flare will be situated in a shorter part of that spectrum band. As to the general tenor of the conclusions, it will not change.

Therefore, on the basis of the material brought up, the following conclusions can apparently be derived :

1.- Comparison of ionosphere effects with the rocket measurements of X-ray radiation point to the fact that indirect measurements of short-wave radiation can be successfully carried out alongside with the direct ones.

2.- The spectral distribution of the intensity of X-ray emission of flares is different for various flares.

3.- Certain solar flares are characterized by an appreciable increase in intensity of X-ray radiation in the shortwave region (from 0.1 to 1.0 A).

It is natural that all the indicated deductions must be verified by means of a larger experimental material, involving the data obtained aboard rockets and satellites.

*** THE END ***

14 May 1962.

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